Project Report

Program 1
Greening the Built Environment

Project
Housing Sustainability Performance

Project Number	
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PROJECT OVERVIEW

PROJECT AIMS

This project provides initial data on simulated thermal performance as designed, and actual performance as constructed, of a number of houses in subtropical and tropical Queensland. It provides some insight into the impact of housing sustainability performance on occupants. The purpose of the project was to expand and deepen industry engagement and to develop further data which can be used beyond this project for further project proposals.

PROJECT METHODOLOGY

The project used a case study methodology to focus on three specific factors:

1. Comparison of simulated thermal performance with measured thermal performance.
2. Correlation of measured thermal performance with occupant feedback.
3. A literature review of the maintenance of energy efficiency requirements of regulation as applied in Queensland homes (i.e. insulation, lighting, water heating, outdoor areas, photovoltaics)

PROJECT COLLABORATION

This project is interlinked with

- "*A Framework for Adaptation of Australian Households to Heat Waves*", a National Climate Change and Adaptation Research Facility (NCCARF) project involving University of South Australia, University of Sydney, Queensland University of Technology and University of Adelaide, and
- QUT – Metecno Pre-Linkage Project

OUTPUTS

ARC LINKAGE PROJECT SUBMISSION NOVEMBER 2012

LP130100650: *From innovators to mainstream market: a toolkit for transforming Australian housing and maximising sustainability outcomes for stakeholders.*
Universities: QUT, Curtin, Karlsruhe Institute of Technology (Germany)
Industry partners: Building Commission WA, WA Department of Finance, Stockland Development, Bondor (a division of Metecno), Finlay Homes

SBE FOUNDATION PROJECT SUBMISSION NOVEMBER 2012

Project 1.29 *Strategies and Solutions for Housing Sustainability*

ACADEMIC PUBLICATIONS

Miller, W., & Shah Nazari, H. (2012). *Occupant comfort, the housing industry and electricity infrastructure: understanding the synergies.* Proceedings of 5th International Urban Design Conference - Opportunistic Urban Design Melbourne 2012, Melbourne, Australia.

Saman, W., Boland, J., Pullen, S., de Dear, R., Soebarto, V., **Miller, W**., . . . Deuble, M. (2013 – in final preparation for submission in March). *A Framework for Adaptation of Australian Households to Heat Waves*. Adelaide: University of South Australia, for the National Climate Change Adaptation Research Facility.

Miller, W. (accepted 2013). *Analysis of the design-construction supply chain in the thermal performance of sub-tropical and tropical housing.* Paper to be presented at the World Building Congress (5-8 May) 2013, Brisbane, Australia.

PART A: BUILDING PERFORMANCE

PARTICIPATING HOUSEHOLDS

A total of 26 households were recruited for a twelve month building performance assessment. Recruitment occurred between December 2011 and April 2012.

South-east Queensland = 20 households
Inland suburbs were targeted, as they do not experience cooling sea breezes. These suburbs tend to be hotter in summer, and colder in winter, than suburbs closer to the Pacific Ocean. They are also the largest growth areas for new residential development. They are represented in the National House Energy Rating Scheme (NatHERS) by Climate Zone 9 (based on Bureau of Meteorology weather station Amberley (ID 040004))

- Brisbane south-western suburbs / Ipswich (16)
- Brisbane north-western suburbs (1)
- Gold Coast inland suburbs (3)

Townsville = 6 households
Five of the recruited households are in new residential developments to the north and north-west of Townsville CBD. The sixth household is located in a western suburb. These houses are in NatHERS climate zone 5, BOM weather station ID 032040.

Selection criteria consisted of dwellings constructed since 2005 (or major renovations since that period) and dwellings equal to, or less than, the median house size for new Queensland homes (230m^2). Households were recruited via direct mail campaigns, network emails and word of mouth.

HOUSEHOLD DEMOGRAPHICS

Household demographics (Figure 1) represent a range of family types from single adults, households of adults only, and households of adults and children. A quarter of participating households had children under school age. 50% of the households were single income households (i.e. only 1 adult working full time). No households had an annual gross income of less than $50,000. Half of the households had an annual gross income of greater than $110,000 (usually represented by more than 1 full time working adult).

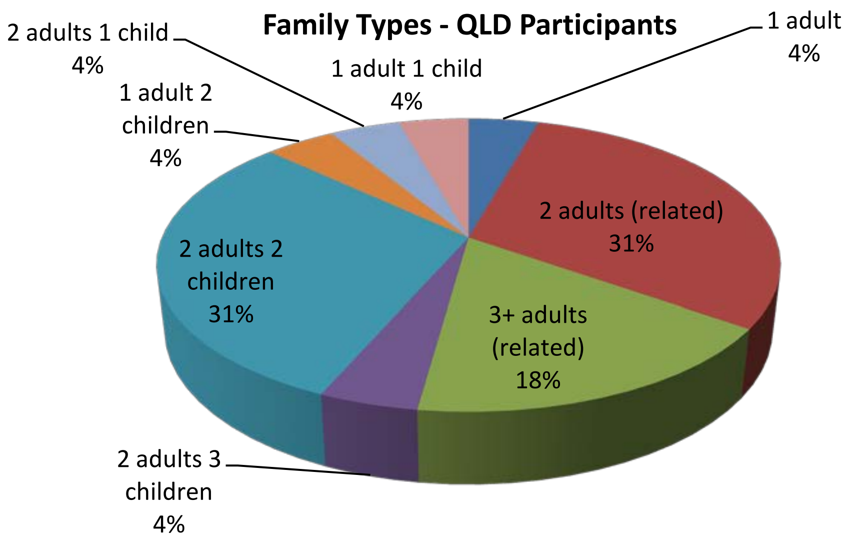

FIGURE 1: HOUSEHOLD DEMOGRAPHICS

HOUSE CONSTRUCTION DETAILS

The recruited houses (refer to Table 1) represent the diversity of housing that make up the Queensland housing market:

Construction type

- 33% are elevated construction whilst the remainder are slab-on-ground (SOG).
- 33% are light weight construction, with the remainder heavy weight construction (brick veneer or cement block)
- Most homes a single storey (2 storey homes are highlighted in Table 1)

Cooling technologies

- Six of the homes have no air-conditioning (marked with an asterix in Table 1). These houses were included in the study to provide a comparison of occupant comfort strategies compared with air conditioned houses. (This is consistent with regional statistics: 26% of SEQ homes are thought to have no air conditioners).
- Split systems were the predominant air conditioner type.
- Four households (20% of air conditioned houses) had an air conditioner in the living room only. Of those houses with more than one air-conditioner, the majority had a split system in each of the bedrooms (with a few having a split system in only the main bedroom).
- The majority of houses had ceiling fans in living areas and bedrooms.

TABLE 1: QUEENSLAND HOUSES UNDER STUDY

ID	Location	Family (Adults, Children)	House construction type	Construction yr (renovation)
QLD 1	Ipswich	1A	SOG, brick veneer	2003 (2007)
QLD 2	Ipswich	2A, 2C	SOG, brick veneer	2008
QLD 3	Ipswich	2A, 3C	SOG, brick veneer	2009
QLD 4	Ipswich	3A	SOG, mixed	2007
QLD 5	Ipswich	2A, 2C	SOG, brick veneer [SOG, lightweight, 2 storey townhouse]	2008 [2012]
QLD 6	Ipswich	1A, 1C	SOG, brick veneer	2009
QLD 7	Brisbane south-west	5A	Elevated, lightweight	2008
QLD 8	Ipswich	1A, 2C	SOG, brick veneer	2009
QLD 9	Ipswich	2A, 2C	Elevated, lightweight	2006 (2010)
QLD 10	Brisbane south-west	2A, 1C	SOG, brick veneer	2009
QLD 11*	Brisbane south-west	2A, 2C	Elevated, lightweight	2011
QLD 12*	Brisbane south-west	2A, 2C	Elevated, lightweight	(2009)
QLD 13	Brisbane south-west	2A, 1C	SOG, brick veneer	2005
QLD 14	Brisbane south-west	2A	SOG, brick veneer	c. 2006
QLD 15	Brisbane south-west	3A	SOG, brick veneer	Pre 2006
QLD 16	Brisbane south-west	2A	SOG, brick veneer	c. 2006
QLD 18*	Gold Coast – inland	2A	Elevated, lightweight	2009
QLD 19*	Gold Coast – inland	2A	Elevated, lightweight	2008
QLD 20*	Gold Coast – inland	2A	Elevated, mixed weight	2008
QLD 21*	Brisbane north-west	2A, 2C	SOG, lightweight	2011
QLD 22	Townsville	2A	SOG, lightweight	2011
QLD 23	Townsville	2A, 2C	Elevated, lightweight	2011
QLD 24	Townsville	2A	SOG, cement block	2006
QLD 25	Townsville	2A, 1C	SOG cement block	2010
QLD 26	Townsville	3A, 1C	SOG cement block	2010
QLD 27	Townsville	2A	SOG cement block	2011

PERFORMANCE ASSESSMENT STRATEGIES

A range of performance assessment strategies (Table 2) were applied to each house.

BUILDING SIMULATION

BersPro 4.2, accredited building simulation software under the National House Energy Rating Scheme (NatHERS), was used to simulate the thermal performance. This is the predominant software used in Queensland for building regulatory purposes. Three simulations were conducted for each available house: regulatory mode (as per NatHERS), regulatory mode with improved ventilation modelling, and free-running mode (assuming no air-conditioning).

THERMAL IMAGING AND AIR-INFILTRATION

Eleven of the homes in south-east QLD and two of the Townsville homes (plus 2 display homes in Townsville) were subject to thermal imaging and air infiltration tests in January and February 2012. The testing was carried out by Blair Freeman, a certified Building Science Thermographer, Level 2 Air Leakage Technician, and member of AUSPTA (Australian Professional Thermography Association)[1]. Thermal Imaging was conducted according to EnergyLeaks Quickscan EL 1 utilising a FLIR E50bx camera. Air leakage testing was conducted using a **Retrotec 2000** fan, and in accordance with the following standards:

- ATTMA TS1 Issue 2 – Measuring Air Permeability of Building Envelopes
- BS EN13829:2001 Thermal Performance of Buildings
- BINDT – Quality Procedures and Explanatory Notes for Air Tightness Testing

THERMAL PERFORMANCE

Maxim ibutton sensors were installed progressively in each of the 26 houses between January and April 2012. Sensors were programmed to record every 15 minutes, with an accuracy of 0.5^{o}C, and will remain in place until a full year of data is recorded or the end of March 2013. Five or six sensors were placed throughout each house:

- Main living room (temperature and humidity)
- AC outlet in main living room (temperature)
- Main bedroom (temperature)
- Second bedroom or study / office (temperature)
- Outdoor living area (temperature)

AIR-CONDITIONER AND ELECTRICAL LOAD SUB-METERING

WattWatchers is the metering technology selected by the NCCARF project to provide sub-metering and reporting on electricity circuits in participating houses. To date (February 2013), this technology has been installed on 9 of the Queensland houses and is expected to be installed in another 4-7 houses in the next month. Some houses were assessed as unsuitable for this type of metering due to wireless internet access issues. Four of the houses already had alternative sub-metering systems in place.

COMFORT SURVEYS

Participating households completed period comfort surveys initiated by QUT predominantly during periods of warm/hot weather. Surveys were completed either via SMS, online or on paper. The surveys included questions about comfort levels, clothing level and operation of the house (e.g. doors, windows and air conditioners). A total of 335 surveys were completed by Queensland participants between 21st February 2012 and 6th February 2013. Each of

[1] Blair died unexpectedly in September 2012. We wish to acknowledge the significant contribution he made to this study.

these comfort responses was matched with temperature data from the nearest BOM weather station and from temperature data recorded at each house. This data is currently being analysed by the University of Sydney for the NCCARF project and will be reported in the NCCARF project report.

Note that not all strategies could be applied to each individual house due to limitations in access to building plans, availability of houses for physical testing, technical compatibility of metering systems and availability of occupants. Table 2 records the strategies applied to each house. Five households (shown with shaded cells in Table 2) withdrew from the program part way through 2012 for various reasons, including weather damage to the house, change of jobs (and therefore availability) and sale of the house. The remaining households will continue with the program until the end of March 2013 (approximately).

TABLE 2: PERFORMANCE ASSESSMENT STRATEGIES APPLIED TO PARTICIPATING HOUSEHOLDS

ID	Building simulation	Thermal imaging	Air-infiltration	Thermal performance	Comfort surveys	Sub-metering
QLD 1		✓	✓	✓	✓	
QLD 2	✓	✓	✓	✓	✓	✓
QLD 3	✓	✓	✓	✓	✓	✓
QLD 4	✓	✓	✓	✓	✓	✓
QLD 5	✓	✓	✓	✓	✓	✓
QLD 6				✓	✓	
QLD 7		✓	✓	✓	✓	✓
QLD 8	✓	✓	✓	✓	✓	✓
QLD 9		✓	✓	✓	✓	
QLD 10	✓			✓	✓	✓
QLD 11*	✓			✓	✓	✓
QLD 12*				✓	✓	
QLD 13				✓	✓	
QLD 14						
QLD 15				✓		
QLD 16				✓	✓	✓
QLD 18*	✓	✓	✓	✓	✓	✓
QLD 19*	✓	✓	✓	✓	✓	✓
QLD 20*	✓	✓	✓	✓	✓	✓
QLD 21*	✓	✓	✓	✓	✓	✓
QLD 22				✓	✓	
QLD 23				✓		
QLD 24	✓	✓	✓	✓	✓	
QLD 25	✓			✓	✓	
QLD 26	✓			✓	✓	
QLD 27	✓			✓	✓	

THERMAL PERFORMANCE ANALYSIS

Table 3 summarises the simulated and tested thermal and air tightness of each of the houses. The simulated figures (star ratings and heating and cooling loads) are based on actual simulated performance, with no allowances made for small floor area under 200m^2 (as permitted under NatHERS regulations) or for outdoor living spaces or photovoltaic systems (as currently permitted under Queensland building regulations to assist in achieving a nominal six stars). The shaded rows are Townsville houses; unshaded rows are south-east Queensland houses.

TABLE 3: SUMMARY OF THERMAL PERFORMANCE

ID	Star rating	Total MJ/m^2/yr	Heating Load MJ/m^2/yr	Cooling Load MJ/m^2/yr	Thermal tightness	Air tightness (air changes per hr, at 50 Pa)
QLD 1	No building plans				poor	10.5
QLD 2	5.5	76.2	12.7	63.5	fair	10.05
QLD 3	6.5	58.4	17.4	41	fair	8.795
QLD 4	7.5	50.9	13.8	37.1	extremely poor	5.83
QLD 5	6	66.4	34.3	32.1	fair	11.65
QLD 6	No building plans					
QLD 7	No building plans				fair	
QLD 8	5.5	83.2	46.6	36.5	fair	
QLD 9	Not yet simulated				fair	8.581
QLD 10	7.5	47.2	19.3	27.9		
QLD 11*	3.5	79.5	54	25.6		
QLD 12*	No building plans					
QLD 13	No building plans					
QLD 14	No building plans					
QLD 15	No building plans					
QLD 16	No building plans					
QLD 18*	7	32.4	11.6	16.9	fair	
QLD 19*	6	42	16	26	extremely poor	
QLD 20*	9	14.3	6.3	8	good, minor leaks	
QLD 21*	8	32	19.8	12.2	very good, minor leaks	13.85
QLD 22	7.5	94.2	0.7	93.5		6.815
QLD 23	No building plans					
QLD 24	6.5	130	0.5	129.5	fair	
QLD 25	5.5	150.6	0.6	150		
QLD 26	6	128	0.3	127.7		
QLD 27	7	101	0.3	100.8		

BUILDING DOCUMENTATION

In general, the over-arching project (the combined NCCARF, QUT/Metecno, SBE projects) revealed very poor levels of housing documentation. Many occupants did not have copies of their house plans (building documents) despite all homes being relatively new (generally less than 6 years old), and only three households could provide a copy of the energy certificate for the house or provide information on the expected thermal performance of the house (e.g. the star rating).

THERMAL TIGHTNESS

All of the 15 houses subjected to thermography (13 of the houses as shown in Table 2, plus 2 display houses in Townsville) had issues that would make them non-compliant (minor to serious) with the current building regulations and impact negatively on the thermal performance of the building. The common issues found included:

- Poor perimeter coverage (typically 300-600mm around perimeter of internal ceilings), with particularly poor (or zero) coverage in the corners of hip roof designs. (NOTE: Australian Construction Code requires that all insulation covers at least 40% of the external wall top plate to give the desired thermal coverage to suit the dwelling.)
- Patchy (or absent) ceiling coverage in general
- Entry hallways, utility rooms (e.g. bathrooms, toilets, laundry) and bulkheads often not insulated to Australian Construction Code requirements (i.e. as per ceilings.)
- Poor insulation around downlights, exhaust fans, manhole covers
- Doors and windows are weak spots thermally
- Poor / absent insulation of adjoining garages (with shared roof space with living areas)

Two of the homes revealed extensive and serious non-compliance issues that resulted in house owners liaising with the relevant builders to 'make good'.

SIMULATED VERSUS ACTUAL PERFORMANCE

As the data collection period has not yet been completed (i.e. there is not a full year of temperature monitoring for each house), full comparison of simulated versus actual thermal performance is not possible. This will be undertaken progressively as the data is available. Some initial analysis was conducted on a small sample of Ipswich houses. Table 4 shows the key variables of these six homes.

TABLE 4 DEMOGRAPHIC, CONSTRUCTION AND EXPERIENTIAL VARIABLES OF CASE STUDY HOUSES

Indicator		**Range/ Variables**					
		House 1	**House 2**	**House 3**	**House 4**	**House 5**	**House 6**
Number of occupants	*Child*	0	2	3	0	2	1
	Adult	1	2	2	3	2	1
Occupancy		Work from home	Pre-school children at home	Pre-school children at home	Generally unoccupied daytime	Shift work	Shift work
Construction year		2004 / 2008	2007	2009	2007	2007	2006
Total building area (m^2)		198.48	234.84	191.12	155.4	217.4	140.6
Internal living area (m^2)		182.03	173.99	146.64	120.6	166.6	Est. 110
AC system/s		Whole house ducted	Split units	Split unit	Split unit	Split units	Split units
Number of ACs		1	5	1	1	2	2
Other cooling		Ceiling fans	Ceiling fans	Ceiling fans	Ceiling fans	Ceiling fans	Portable fans
AC use during summer		Day: office & living room; whole house when hot weather predicted	Day: living room when <32; night – bedrooms	Living room when <28^0	Living room when <26^0	Living room and main bed when <30^o	Living room and main bed when<30^0
AC thermostat set point		24^{o}C	24^{o}C	24^{o}C	24^{o}C	25^{o}C	24^{o}C
Use of window openings for cross ventilation		Not in summer	Yes; close when AC on	Yes; close when AC on	Sometimes	Sometimes	Sometimes

Analysis of thermal performance during a short period of hot weather (late February, early March 2012) revealed evidence of overheating (i.e. internal temperatures higher than the adaptive comfort band of 18 – 28^{o}C for this climate zone). Whilst more analysis is needed to try to identify why these houses appear to be overheating in summer, initial evaluation suggests several causes:

- Lack of certification that buildings are constructed as designed (e.g. insulation installed as per the design and Australian Construction Code)
- Lack of consideration of the thermal performance of each room (compared with the performance of the house as a whole). For example, the thermal performance of bedrooms in particular needs addressing. NatHERS assumes that bedrooms are unoccupied for much of the day and therefore no cooling energy is applied prior to 4pm. However in the preliminary study, only one house out of six was unoccupied during the day and four of the six houses had occupants who were very likely to regularly use bedrooms during the day and night (e.g. shift workers and young children). Furthermore, the overheating of the bedrooms (and the living rooms) presents challenges for electricity distributors as the cooling of these spaces is likely to occur between 4-8pm, the peak demand time.

PUBLICATIONS

Preliminary analysis of partial data has been conducted and findings presented in two conference papers and the official NCCARF project report. These publications are listed below.

Miller, W., & Shah Nazari, H. (2012). *Occupant comfort, the housing industry and electricity infrastructure: understanding the synergies.* Proceedings of 5th International Urban Design Conference - Opportunistic Urban Design Melbourne 2012, Melbourne, Australia.

Saman, W., Boland, J., Pullen, S., de Dear, R., Soebarto, V., **Miller, W**., . . . Deuble, M. (2013 – in final preparation for submission in March). *A Framework for Adaptation of Australian Households to Heat Waves*. Adelaide: University of South Australia, for the National Climate Change Adaptation Research Facility.

Miller, W. (accepted 2013). *Analysis of the design-construction supply chain in the thermal performance of sub-tropical and tropical housing.* Paper to be presented at the World Building Congress (5-8 May) 2013, Brisbane, Australia.

Part B: Literature Review

Sustainability features in residential buildings can be classified into three main types:

- Design features
- Building materials
- Technologies

A literature review (peer-reviewed published research) was conducted on these topics, focusing on *maintenance* issues relating to these three classifications of sustainability features. Only features impacting on the energy efficiency of residential buildings are included (i.e. energy efficiency requirements in current Queensland legislation, including insulation, lighting, water heating, outdoor areas, photovoltaics). Particular consideration was made of multi-residential buildings (as differentiated from detached housing).

Academic journals in the fields of buildings and energy, energy, renewable energy, life cycle assessment and building performance were reviewed (refer to list of literature reviewed). Overall, very little research literature covers maintenance issues. Even in life cycle assessment methodologies there is typically little delineation between operational costs and maintenance costs. Ortiz et al (2009), in their carbon emission analysis of a Spanish house (50 year life span), estimated that **maintenance contributed only 1.7% to life-cycle carbon emissions**, with building operations contributing 88.9%. This finding, that **maintenance activities have a marginal effect on environmental performance**, is supported by Blom et al (2010).

Invariably studies of low-carbon technology applications to the built environment focus on capital and operational energy costs, the associated payback periods, and barriers created by regulation and the market (e.g. lack of clear targets, and perceived risks) (Atkinson, 2009; Kannan, 2009; Sunikka, 2006).

Four possible reasons for the lack of research literature on this topic are proposed:

1. **Maintenance requirements** for building products, appliances and technologies in general, **are typically provided with specific product manufacturers' documentation and product warranties.**
2. **Maintenance requirements for low-carbon technologies and strategies may not vary significantly from the maintenance requirements of technologies and strategies that they are replacing** (e.g. double-glazed windows do not require any more maintenance than single glazed windows). Even if maintenance requirements of new technology are different, they are not necessarily more onerous than the technologies they are replacing.
3. **There is a perception that product quality, performance and maintenance issues are adequately covered through regulations, standards and market mechanisms** (e.g. warranties). This includes an assumption that products will be supplied with appropriate operation and maintenance information.
4. Research tends to focus on the development of technology, or the early stage diffusion of the technology into the market. There are **very few post-occupancy performance evaluations of buildings and their systems**, and those that do exist **do not explicitly cover maintenance considerations** (which are generally a long term consideration).

In view of this, the following paragraphs provide brief comments on each of the three classifications of energy related sustainability features that could be applied to residential buildings.

DESIGN FEATURES

The best strategy for lowering the carbon intensity of any building's energy operation is to ensure that the building design is optimised to reduce the need for space heating and cooling, and maximise natural light and ventilation (Charron and Athienitis, 2006; European Council for an Energy Efficient Economy, 2009; Marszal et al, 2011). The incorporation of climatically appropriate passive solar design features such as orientation, layout, cross-ventilation and shading, can result in a dramatically reduced energy demand for space cooling (and heating). This is evidenced, for example, in the differing cooling loads shown previously in Table 3. Multi-residential dwellings have advantages over detached housing in that it is typically easier to achieve higher thermal efficiency of the building envelope, due to the reduction in external wall and roof area (compared to internal floor area). These sustainability features do not result in any maintenance issues, and there are no publications on this topic.

Similarly, the inclusion of an outdoor living area does not present any out-of-the-ordinary maintenance requirements. The energy efficiency impact of such outdoor living areas, however, has not yet been proven. That is, there is no empirical evidence supporting a regulatory assumption, in Queensland, that an outdoor living area will result in a decrease in the utilisation of air conditioners for occupant comfort. For this reason, this project measured the ambient air temperature of outdoor living spaces of participating homes. This data has yet to be analysed in relation to occupant usage of these spaces during periods of hot weather.

BUILDING COMPONENTS

Energy efficiency requirements in residential dwellings in Australia currently encompasses building elements specified through the National Construction Code (building envelope thermal performance, including insulation; lighting and hot water systems) and appliances (managed through the Minimum Energy Performance scheme, such as air conditioners, white goods; some electrical goods; pumps etc).

In northern Europe, low-energy components in the building sector include thermal insulation, air-tightness products, windows, doors, solar shading, structural frame components (to reduce thermal bridges), ventilation systems, heat recovery systems, heat pumps, heat distribution systems, pumps, control systems and household appliances (Blomsterberg, 2011). This EU study was focused on the availability of these products within various markets, and the need for further product improvements to enable the very low energy demand in the built environment. There was no discussion on maintenance of the components. Other studies (e.g. Ballaras e al, 2007; Xing, 2011) look at the energy conservation hierarchy of building components, with insulation typically being the highest, followed variously by glazing (e.g. double glazing) and weather stripping (to increase air tightness). These types of products should present very few maintenance issues if installed correctly.

'Cool roof' coatings are another building component that has the potential to increase the energy efficiency of residential buildings, in both new and existing building stock. A 'cool roof' is defined as a roof that, because of its optical and infra-red properties, usually imparted by special coatings, remains at or near ambient temperature under sunny conditions. Special roof coatings are identified by their *solar reflectance*, *thermal emittance* and/or *solar reflectance index* (a combination of the two). Cool Roofs are reported to have multiple benefits including reductions in energy consumption and peak demand, monetary savings, increased thermal comfort in and around buildings, improved operational efficiency of air-conditioners, extended roof life, and enhanced urban environmental quality (Hirano and Fujita, in press; Akbari and Matthews, 2012; Santamouris, 2012).

'LOW ENERGY' TECHNOLOGIES

"Low energy' technologies most likely to be installed in Australian residential buildings include space heating technologies (e.g. solar air collectors, hydronic heating systems), electricity generation technologies (photovoltaics), co-generation technologies (e.g. combined heat and power systems) and 'resource management' and occupant feedback technologies.

Again, no research literature was found that deals specifically with the maintenance of such systems. It appears that both regulators and the market assume that product performance and maintenance is adequately covered through normal market mechanisms of product documentation and warranties, national and international standards, and local regulation.

This assumption may be misguided, however, as shown in post-occupancy evaluations of solar water heating performance and resource monitoring technology in new Queensland houses (Miller and Buys, 2010 a and b). Both of these studies revealed occupant challenges with technology performance and maintenance that appears to be due to lack of integrated systems thinking in the design and installation of the products, and a lack of responsibility and accountability for performance outcomes on the part of regulators, manufacturers, suppliers and installers.

Based on these experiences, it is expected that similar performance and maintenance challenges are likely to exist in Australian homes in relation to photovoltaic systems. In Queensland, with the requirement for wiring of systems in a net-metering configuration, the performance of such systems is not possible (for either the network or the home owner). Post-occupancy evaluation of the performance of the growing number of residential PV systems is extremely challenging due to this technical requirement.

A few studies have been conducted in relation to the performance of combined heat and power systems that may have application in Australian climates that have a demand for both heating (space and hot water) and electricity. Several studies, in the northern hemisphere, have attempted to compare CHP systems (energy efficiency, cost and life cycle benefits) with 'traditional' heating and electricity sources (Kaarsberg et al. 200; Thiers and Peuportier, 2012; Onovwiona and Ugursal, 2006; Uduman, 2010; Keelan, 2010). Due to differences in climate, building construction methods, building standards, and markets, these studies have little direct applicability to the Australian residential market.

SUMMARY OF LITERATURE REVIEW

In summary, this review has shown that there is very little research literature that covers maintenance issues, and that maintenance is considered to be a very minor component of overall building energy efficiency and carbon emissions. Maintenance of low-energy building components and technologies appears to have been left in the realm of standard market mechanisms. This results in residential building owners to having to compare manufacturers' claims on product performance and maintenance requirements, in order to make decisions regarding the viability of particular components for specific building applications. There is some evidence to suggest a need for some performance verification to be conducted to validate performance outcomes in terms of energy efficiency and reduction in carbon, especially in the Australian market.

Literature Reviewed

Akbari, H., & Matthews, H. D. (2012 (in press)). Global cooling updates: reflective roofs and pavements. *Energy and Buildings*.

Atkinson, J., Jackson, T., & Mullings-Smith, E. (2009). Market influence on the low carbon energy refurbishment of existing multi-residential buildings. *Energy Policy, 37*(7), 2582-2593.

Balaras, C., Gaglia, A., Georgopoulou, S., Sarafidis, Y., & Lalas, D. (2007). European residential buildings and empirical assessment of the Hellenic building stock, energy consumption, emissions and potential energy savings. *Building and Environment, 42*(3), 1298-1314.

Blengini, G. A., & Di Carlo, T. (2010). Energy-saving policies and low-energy residentail buildings: an LCA cse study to support decision makers in Piedmont (Italy). *The International Journal of Life Cycle Assessment, 15*(7), 652-665.

Blom, I., Itard, L., & Meijer, A. (2010). LCA-based environmental assessment of the use and maintenance of heating and ventilation systems in Dutch dwellings. *Building and Environment, 45*(11), 2362-2372.

Blomsterberg, A. (2011). Availability of components for very low energy residential buildings on the North European Building Market *NorthPass* Intelligent Energy Europe, European Commission.

Charron, R., & Athienitis, A. (2006). Design and Optimization of Net Zero Energy Solar Homes. *ASHRAE Transactions, 112 Part 2*(2), 285-295.

De Silva Jardim, C., Ruther, R., Salamoni, I. T., de Souza Viana, T., Rebechi, S. H., & Knob, P. J. (2008). The strategic siting and the roofing area requirements of building-integrated photovoltaic solar energy generators in urban areas in Brazil. *Energy and Buildings, 40*(3), 366-370.

Energy consumption and greenhouse gas emissions related to the use, maintenance and disposal of a residential structure. (2005). *Wood and Fiber Science*(37), 128-139.

European Council for an Energy Efficient Economy. (2009). Net zero energy buildings: definitions, issues and experience *Steering through the maze #2*. Stockholm.

Henderson, A. (2009). Market share: feasibility study for a multi-family unit infill green development. *Cardinal Scholar*. doi: http://liblink.bsu.edu/uhtbin/catkey/1508541

Hirano, Y., & Fujita, T. (In Press). Evaluation of the impact of the urban heat island on residential and commercial energy consumption in Tokyo. *Energy*.

Hong, T., Koo, C., & Park, S. (2012). A decision support model for improving a multi-family housing complex based on CO2 emission from gas energy consumption. *Building and Environment, 52*, 142-151.

Kannan, R. (2009). Uncertainties in key low carbon power generation technologies - Implication for UK decarbonisation targets. *Applied Energy, 86*(10), 1873-1886.

Kaarsberg, T., Fiskum, R., Deppe, A., Kumar, S., Rosenfeld, A., Romm, J., & Gielen, L. (2000). Combined Heat and Power for Saving Energy and Carbon in Residential Buildings: Lawrence Berkeley National Laboratory.

Keelan, A. (2010). Comparison of hydronic heating systems in multi-residential apartment buildings. *University of British Columbia*.

Marszal, A., Heiselberg, P., Bourrelle, J., Musall, E., Voss, K., Sarton, L., & Napolitano, A. (2011). Zero Energy Building - A review of definitions and calculation methodologies. *Energy and Buildings, 43*(4), 971-979.

Marszal, A. J., & Heiselberg, P. (2011). Life cycle cost analysis of a multi-storey residential Net Zero Energy Building in Denmark. *Energy, 36*(9), 5600-5609.

Matics, J., & Krosti, G. (2008). Micro combined heat and power home supply: prospective and adaptive management achieved by computational intelligence techniques. *Applied Thermal Engineering, 28*(16), 2056-2061.

Miller, W., & Buys, L. (2010a). *Gas boosted solar water heaters: Queensland case studies of installation practices in new homes*. Paper presented at the Solar2010 - the 48th AuSES Annual Conference, Canberra, Australia.

Miller, W., & Buys, L. (2010b). *Householder experiences with resource monitoring technology in sustainable homes.* Paper presented at the OZCHI 2010: 22nd Annual Conference of the Australian Computer-Human Interaction, Queensland University of Technology, Brisbane.

Onovwiona, H. I., & Ugursal, V. O. (2006). Residential cogeneration systems: review of the current technology. *Renewable and Sustainable Energy Reviews, 10*(5), 389-431.

Ortiz, O., Bonnet, C., Bruno, J. C., & Castells, F. (2009). Sustainability based on LCM of residential dwellings: a case study in Catalonia, Spain. *Building and Environment, 44*(3), 584-594.

Perry, S., Klemes, J., & Bulatov, I. (2008). Integrating waste and renewable energy to reduce the carbon footprint of locally integrated energy sectors. *Energy, 33*(10), 1489-1497.

Ramesh, T., Prakash, R., & Shukla, K. K. (2010). Life cycle energy analysis of buildings: an overview. *Energy and Buildings, 42*(10), 1592-1600.

Santamouris, M. (2012). Coolng the cities - A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. *Solar Energy, 2012 In Press*.

Sunikka, M. (2006). Energy efficiency and low-carbon technologies in urban renewal. *Building Research & Information, 34*(6), 521-533.

Thiers, S., & Peuportier, B. (2012). Energy and environmental assessment of two high energy performance residential buildings. *Building and Environment, 51*, 276-284.

Uduman, V. (2010). Lifecycle space heating analysis of a 60 unit multi-residential building. *University of British Columbia*.

Xing, Y., Hewitt, N., & Griffiths, P. (2011). Zero carbon buildings refurbishment - a hierarchical pathway. *Renewable and Sustainable Energy Reviews, 15*(6), 3229-3236.

Zavri, M. S., Zarnic, R., & Selih, J. (2009). Multicriterial sustainability assessment of residential buildings. *Technological and Economic Development of Economy, 15*(4), 612-630. doi: 10.3846/1392-8619.2009.15.612-630